Low-Noise Preamplifier Design for NMR

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An important component in any nuclear magnetic resonance (NMR) imaging or spectroscopy system is a low-noise preamplifier. The required minimization of its noise figure can be obtained only by careful design. It must go hand in hand with an optimization of the "noise figure" of the NMR receive coil. The latter requires that the coil quality factor Q is made as high as possible. Other receiver system components such as cables, protection circuits, matching networks, transmit/receive (T/R) switches, etc., should not be neglected in a low-noise design. They can easily add many tenths of a dB to the overall receiver noise figure.

The most critical item in a low-noise preamplifier is its input device. Bipolar transistors have the advantage of a relatively large bandwidth at higher frequencies (20-200 MHz). They must be selected for a high current gain, a large gain-bandwidth product F_T of several Gigahertz and especially a low base-region bulk resistance. The latter can be reduced by paralleling two or more transistors. With their high input impedance, juntion field-effect transistors are suitable for low-noise narrow-band preamplifiers. They should exhibit a high transconductance which increases with the electron mobility in the channel. Since the latter is much higher in gallium-arsenide than in silicon GaAs-MESFETs are also good candidates for low noise NMR preamplifier designs.

As far as circuit design is concerned, the following rule should be obeyed: eliminate all parasitic series or parallel impedances between base-emitter or gate-source terminals. This implies that, for example, by-passed emitter resistors must not be used and biasing resistors have values very high compared to the transistor input impedance.

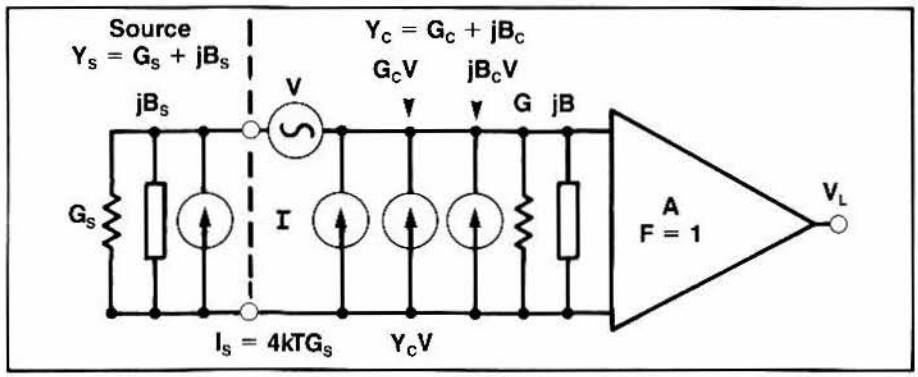

Figure 1. Equivalent amplifier noise circuit including correlation between voltage and current noise source.

Quantitative Design Criteria

The expanded noise equivalent circuit of a preamplifier or its input transistor is shown in Figure 1. $Y_s = G_s + jB_s$ is the source admittance producing the noise current I_s. $Y = G + jB$ is the input admittance of the noiseless (F=1) ideal amplifier of voltage gain A. The amplifier noise is in good first-order approximation represented by the input related equivalent noise voltage and current generators V and I. At higher frequencies they may be partially correlated, an effect which can be represented by the additional current generators (YC) V = (GC+jBC)V where YC is the so-called correlation admittance. Table 1 summarizes the important noise formulas.

The noise figure F defined as the ratio of the total amplifier output noise due to the source resistor only is given by Equation 1. F is minimized by choosing an optimum source admittance $Y_s = G_s + jB_s$ as given by Equation 3. The minimum noise figure obtainable is expressed in Equation 4. The following relationship (Equation 5) shows that the noise has a parabolic dependence on the source susceptance B_s. The same is partially true for G_s. It is interesting to note that the formulas for F do not explicitly depend on the input admittance Y. Its effect is contained the noise generators V and I. In

$$F = 1 + \frac{V^2|Y_s + Y_o|^2 + I^2}{I_s^2} = \text{Minimum}$$

$$\partial F/\partial B_s = 0 \qquad \partial F/\partial G_s = 0$$

$$B_s(OPT) = -B_s \qquad G_s(OPT) = \frac{I^2 + G_c^2V^2}{V}$$

$$F_{MIN} = 1 + \frac{V^2}{2kT}(G_s(OPT) + G_c)$$

$$F = F_{MIN} + \frac{V^2}{4kTG_s}[(G_s(OPT) - G_s)^2 + (B_s(OPT) - B_s)^2]$$

$$Y_c = 0: \qquad G_s(OPT) = |G + jB| \cdot \frac{V_L(G_s=0)}{V_L(G_s=00)}$$

Table 1. Noise formulas.

many cases, especially at lower frequencies, the correlation admittance Y_c is negligible. The optimum source conductance $G_c(opt)$ is then given by the simple expression I/V.

The analysis suggests a simple algorithm for determining the optimum source admittance $Y_s(opt)$ to minimize the noise figure F:

a. Determine the preamplifier input admittance Y = G+jB.
b. Measure the output RMS noise voltage VL(G_s = oo) for a shorted input and VL (G_s = 0) for open-circuited input.
c. Determine from Equation 6 a trial optimum source conductance $G_s(opt)$.

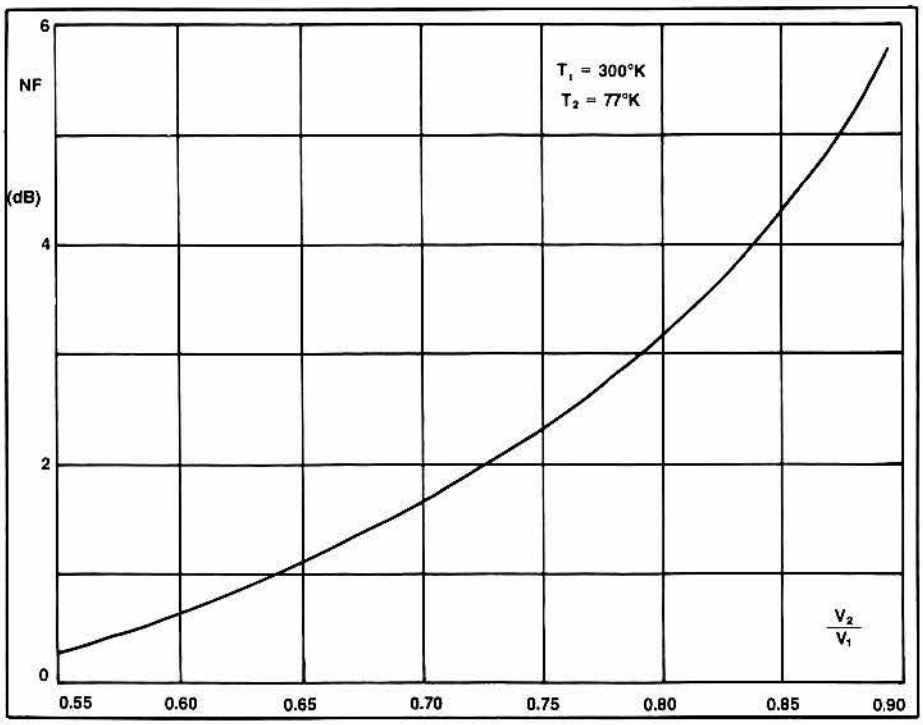

Figure 2. Liquid nitrogen method: Noise figure as a function of the noise voltage ratio V_2/V_1.

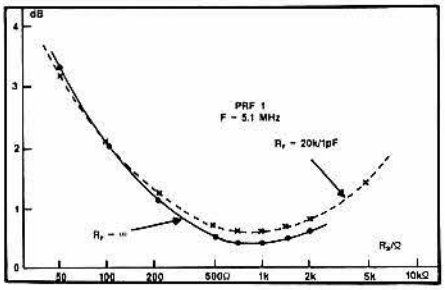

Figure 3. Noise figure vs. source resistor.

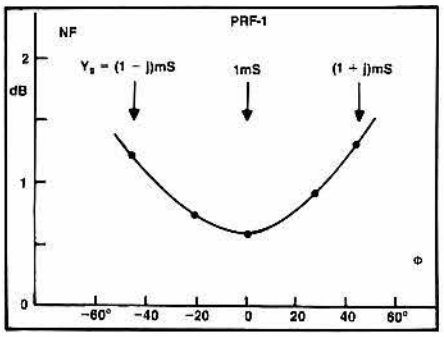

Figure 4. Noise figure as a function of the source admittance phase angle.

d. Measure the noise figure with this source resistor as a function of parallel source susceptance B_s. The value of B_s which minimizes the noise figure is $B_s(opt) = -B_c$.
e. Repeat step b with $B_s = B_c$ and obtain the final value of $G_s(opt)$ which will not be much different from the previously determined one.

It is interesting to note that $B_s(opt)$ is independent of G_s and that in the above procedure it was necessary to determine the correlation explicity. Note that if there is no correlation ($Y_c = 0$) then the optimum source impedance is real and simply given by $R_s = 1/G_s = V/I$.

In order to minimize the preamplifier and the NMR system noise figure it is now important that the receiver coil input impedance is matched by a transformation network to the optimum source admittance given by Equation 3 or 6 in Table 1. The question may arise: What should the input impedance Y of the preamplifier be? Since the formulas for the noise figure and the optimum source admittance $Y_s(opt)$ are independent of Y, the answer is: It does not matter as long as the source (in an NMR system the receiver coil) is matched to $Y_s(opt)$. Since the input impedance of NMR head or body receiver coils is dependent on the size of the patient to be imaged one can use a variable matching network in order to minimize the noise figure or one should use a preamplifier with a very low F.

Measurement Techniques

Since the NMR system operators have liquid nitrogen available in their facilities the so-called two-temperature method of noise figure measurement is very suitable. The preamplifier output noise voltage is measured with the source resistor $R_s = 1/G_s$ first at room temperature T1, (V1), and then dipped into liquid nitrogen (T2 = 77 degree Kelvin, V2). From the curve of Figure 2 (courtesy of Dr. Howard Hart, GE-CRD) and the output noise figure ratio V2/V1 the noise figure F is obtained. The advantage of this method is its low cost and its suitability for noise measurements in a complete NMR system. It also permits an easy determination of F as a function of source resistance without impedance transformation networks. Accurate measurements can be made with the HP-8970A noise figure meter (10-1500 MHz), but only in a 50 ohm system. A comparison between the two methods resulted in good agreement. For all NMR low-noise preamplifier measurements one should use only the HP346A and not the 346B noise source.

In Figure 3 the measured noise figure is shown as a function of source resistance. $R_s = 1/G_s$ for a preamplifier of a low-field NMR system (0.12 Tesla, 5.1 MHz). A cascade configuration of 2 junction field-effect transistors (U-310) is used in the input stage. The optimum source resistance is approximately 750 ohm. Feedback damping has been employed in order to increase the bandwidth of the receiver coil without degrading the noise performance too much. It is interesting to note that $R_s(opt)$ remains the same with and without feedback RF = 00) whereas the input impedance changes drastically from 1700 ohm, −82 degrees to 250 ohm, 22 degrees. This preamplifier was connected directly to an NMR receive coil tuned to Z_{in} = 750 ohm. For RF = 00 a noise figure of F = 0.5 dB and for RF = 20 kohm//1 pF, F = 0.7 dB was obtained. These measurements demonstrate also that the optimum source resistor for junction field-effect transistors relatively high.

Figure 4 shows F at 5.1 MHz as a function of the source admittance phase angle. For $\Phi = \pm 45$ degree a capacitor or inductor having a reactance of X = 1000 ohm was connected in parallel to a source conductance of 1mS. The minimum of the noise figure F occurs for $\Phi = 0$ indicating that the correlation admittance Y_c is zero. This means that the input related noise voltage and current generators V and I in the equivalent circuit of Figure 1 are un-

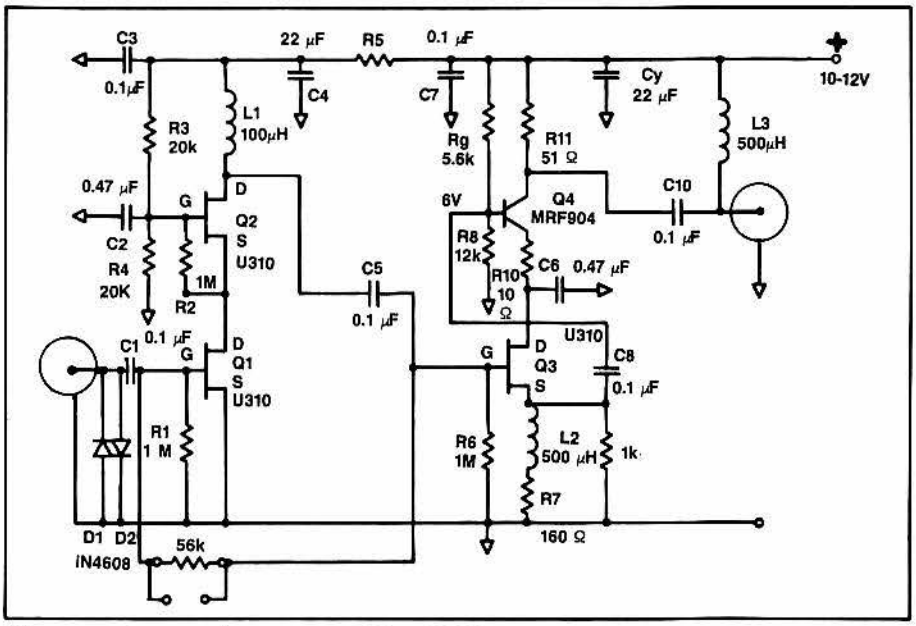

Figure 5. Low-noise preamplifier PRF-1.

correlated. The curve demonstrates that even relatively small deviations from the optimum source conductance by a capacitive or inductive component results in a noise figure degradation of several tenths of a dB. One concludes that for noise optimization it is necessary to control especially the phase angle of the source admittance Y_s. In practical terms this means that a few undesired picofarads in parallel with a preamplifier input can degrade F. On the other hand Figure 3 demonstrates that deviations from G_s(opt) are not that critical because that curve has a relative broad minimum. Figure 5 shows the circuit diagram of this J-FET preamplifier.

At higher frequencies bipolar transistors can be used, especially if a large bandwidth is desired, for example for a preamplifier covering the imaging and the spectroscopy frequencies. (64, 59, 26, 16 MHz). The optimum source resistor is much lower (R_s(opt) = 40 – 100). Figure 6 shows the frequency response of the noise figure for an amplifier using MA-42197 bipolar devices demonstrating that F-values of less than 1 dB can be achieved over a large frequency range. In Figure 7 the noise figure is plotted as a function of the source resistor and the source susceptance for 64 MHz.

Figure 8 demonstrates an example of a preamplifier for which the correlation admittance Y_c is not zero. The minimum noise figure occurs for a source susceptance of $B_s = -3$mS (Parallel inductance with a reactance of XL = 330 ohm). By not neglecting the correlation effect expressed by the correlation admittance $Y_c$one obtains in this case a noise figure improvement of about 0.2 dB. This amplifier used a by-passed emitter resistor in the first stage which probably caused the noise correlation.

Summary

In order to obtain good NMR image quality low-noise preamplifiers are required. With careful design and by providing the optimum source impedance noise figures of 0.5 dB can be achieved. At higher frequencies the correlation between V and I in the noise equivalent circuit should not be neglected if the noise figure is to be minimized.

References

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(2) W.A. Edelstein, P.A. Bottomley and L.M. Pfeiffer, "A Signal-to-noise calibration procedure for NMR imaging systems," *Med Phys.* 11, 180, (1984).

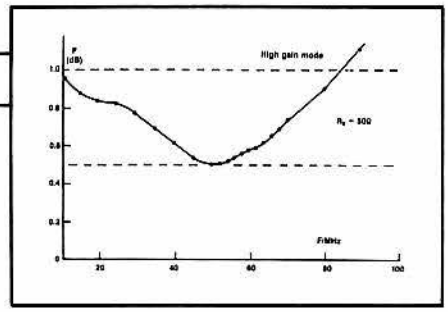

Figure 6. LNA-V-1: Noise figure F vs. frequency.

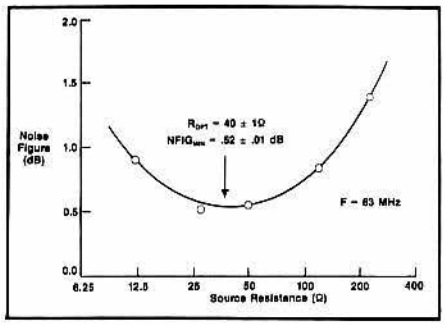

Figure 7a. Noise figure vs. source resistance.

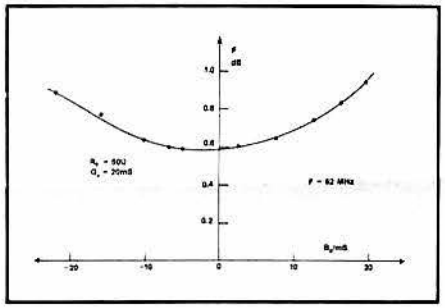

Figure 7b. LNA-V-1: Noise figure vs. source susceptance.

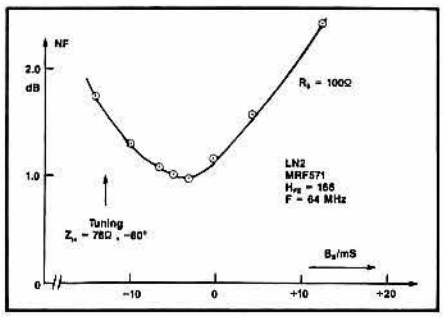

Figure 8. Noise figure vs. source susceptance.

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